



Demonstration of Thermoacoustic Power Sensor

Nuclear Science and Engineering Division

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ANL-ART-180
Rev: 0

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September 2019

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EXECUTIVE SUMMARY

The goal of this project is to develop and demonstrate a thermoacoustic power sensor (TAPS) for Sodium-cooled Fast Reactor (SFR), with potential application also envisioned to other nuclear technologies such as Lead-Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), in addition to Light Water Reactors (LWRs). The project was led by Westinghouse Electric Company, LLC (Westinghouse) and carried out in collaboration with Argonne National Laboratory (ANL) and the University of Pittsburgh. A TAPS is a passive (self-powered), non-invasive (wireless) sensor envisioned for measuring key parameters, such as local temperature and neutron flux, in a nuclear reactor core. The sensor generates pressure waves (i.e., sound waves) with a frequency and amplitude dependent upon nuclear operating conditions (coolant temperature or power changes). The acoustic waves are able to travel through the core and associated structures, and reach to the detector network placed outside of the reactor vessel. These detectors require a very small amount of power which, during loss of power events, can be provided for example by harvesting gamma radiation energy, thus resulting in a monitoring system that can function both during normal operation and during loss of power events.

Westinghouse and the University of Pittsburgh designed and fabricated TAPS prototypes for Argonne National Laboratory (ANL) to carry out in-sodium testing to evaluate the effects of sodium on the TAPS and the performance of the TAPS technique in sodium. Argonne received a TAPS prototype from Westinghouse, and the prototype was modified such that it can be installed into the test vessel and function in sodium at elevated temperature without potentially leaking. A water mockup test apparatus was constructed to validate proper working of the prototype. An instrumentation and control (I&C) system, running on the NI LabView platform, was developed to: 1) operate both the water mockup test and the in-sodium test facility; and 2) process and analyze the received acoustic signals from an array of accelerometers and the Argonne sodium-submersible high-temperature acoustic sensor. The prototype was successfully tested in a water bath at different temperatures. Water mockup tests demonstrated that the TAPS prototype is working properly and its resonance frequency changes linearly with the coolant (water) temperature.

The design and construction of a TAPS test apparatus and the modification of the Argonne USV sodium test facility were completed. The TAPS test apparatus was also successfully integrated with the Argonne USV sodium test facility. The TAPS prototype developed by Westinghouse and a sodium-submersible high-temperature acoustic sensor developed by Argonne are both installed into the TAPS test vessel. Both sensors were tested successfully after a leak testing of the TAPS test apparatus. Under the ambient condition and within argon cover gas, the preliminary tests clearly demonstrated that both sensors detected the TAPS resonance frequency at 1407.2 Hz, which confirms that the TAPS prototype and the two sensors are working properly.

The in-sodium test of the TAPS prototype has been delayed due to the modification, construction, and integration of the USV sodium test facility and the TAPS and ISHM test apparatuses, as well as the required formal safety review and operational approval of the USV-TAPS-ISHM sodium test facility. The sodium test facility is currently in a standby condition and is purged with argon cover gas at a pressure slightly higher than the ambient (~2 psig). Before transferring sodium, the secondary containment will be filled with vermiculite for thermal and electrical insulation. Sodium will be transferred into the vessel for in-sodium testing once the facility is formally approved for operation. Nevertheless, the results of the water mockup tests and the preliminary tests carried out within argon cover gas clearly demonstrate that the TAPS technology has the characteristics to provide continuous self-powered measuring and monitoring of the power level, power distribution, and temperature distribution of an SFR core accurately and in real-time using sensors positioned either outside or inside the core.

Future tasks of in-sodium testing and performance evaluation of the TAPS technique are presented. The tasks included the investigation of: 1) the effects on different thermoacoustic behavior of sodium relative to water 2) the effects that higher temperature and sodium flow have on TAPS performance; 3) the performance of the different sensor-receiver systems positioned inside or outside the vessel; and 4) assessing the effects of potential signal attenuation/distortion and interference between signals from the TAPS and the components of the facility for ultimate application in a nuclear reactor.

Acknowledgments

The work reported here was sponsored by the U.S. Department of Energy (DOE) Office of Nuclear Energy's Advanced Reactor Technologies (ART) program. The TAPS team would like to thank Mr. Christopher Grandy for his guidance and technical direction throughout the course of this effort.

A special acknowledgement of thanks goes to Mr. Thomas Sowinski, Fast Reactor Program Manager for the DOE-NE ART program, during this work and to Dr. Robert Hill, the National Technical Director for Fast Reactors for the DOE-NE ART program, for their consistent support of the Advanced Concepts work.

A special gratitude to our collaboration team, especially to Mr. Michael Heibel, Mr. Jorge Carvajal, and Dr. Paolo Ferroni of Westinghouse Electric Company, LLC, and Professor Jeffrey Viperman of the University of Pittsburgh, for their crucial role of the design and fabrication of a TAPS prototype as well as valuable assistance and suggestions.

Argonne is a U.S. Department of Energy Laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357.

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Acronyms and Abbreviations

A/D	Analog-to-Digital
ANL	Argonne National Laboratory
ART	Advanced Reactor Technology
BNR	Breazeale Nuclear Reactor
BWR	Boiling Water Reactor
C&D	Control and Display
DAQ	Data Acquisition
DOE	U.S. Department of Energy
DOE-NE	Office of Nuclear Energy in the Department of Energy
FBR	Fast Breeder Reactor
FEM	Finite Element Model
FFT	Fast Fourier Transform
FY	Fiscal Year
I&C	Instrumentation and Control
ID	Inner Diameter
ISHM	In-sodium Hydrogen Meter
IST	Imaging and Sensing Technologies
METL	Mechanism Engineering Test Loop
NI	National Instruments TM
OD	Outer Diameter
PWR	Pressurized Water Reactors
SEA	Statistical Energy Analysis
SFR	Sodium-Cooled Fast Reactor
SMS	Signal Measuring System
SS	Stainless Steel
TAPS	Thermoacoustic Power Sensor
TC	Thermocouple
USV	Under-sodium Viewing

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1 INTRODUCTION

For operation optimization, cost efficiency, and safety, it is important to measure and monitor the operating conditions in real-time of a nuclear reactor core. The Thermoacoustic Power Sensor (TAPS) is a self-powered, wireless sensor that could be used for real-time, *in-situ* measurement of key parameters, such as local temperature and neutron flux, in a harsh environment, such as reactor core of a Sodium-Cooled Fast Reactors (SFR), Lead-Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), in addition to Light Water Reactors (LWRs). The wireless TAPS is also applicable for *in-situ* temperature monitoring of dry casks for used fuel storage. A TAPS is essentially a thermoacoustic engine that is encapsulated inside an instrumentation tube and heated by an integral nuclear-powered heater, for example, either a fuel pellet or a gamma-harvesting material. The instrumentation tube consists of a heat source (hot end), a ceramic stack, and an acoustic resonator (cold end) and is filled with a noble gas mixture. The acoustic (sound) waves, generated by the TAPS, propagate through the reactor coolant and through the reactor core and in-vessel structure, and then are measured by acoustic receivers located on the outside of the reactor vessel. The wireless-transmitted acoustic signal is then amplified, filtered, and processed by a signal conditioning and data acquisition (DAQ) system. Sound wave amplitude corresponds to the local radiation flux in the core, and the wave frequency is proportional to the local coolant temperature. An array of TAPSs distributed throughout a reactor core is envisioned to provide wireless, real-time measurements of the local coolant temperature and neutron flux conditions as a function of position.

The objective of this project is to develop and demonstrate a TAPS for in-situ, real-time reactor power and/or core temperature monitoring of an SFR. The workscope includes two major tasks: 1) water mockup testing of a TAPS prototype; and 2) in-sodium testing of a TAPS prototype. Each task includes design and construction of a laboratory pilot test apparatus and performance evaluation of the TAPS prototype, which is supplied by Westinghouse Electric Company, LLC (Westinghouse). This report documents the progress in the development and performance evaluation of the TAPS prototype. Section 2 lists the FY19 workscope and Section 3 describes the working principle of the TAPS. The design and fabrication of a TAPS prototype are reported in this section. Section 4 documents the design and construction of a water mockup test apparatus. The test apparatus consists of a mockup test vessel, a hydrophone, an Argonne high-temperature acoustic sensor, a TAPS prototype, an accelerometer, a heating device, a heating controller, and a data acquisition (DAQ) system. This section also reports and analyzes the results of water mockup testing of the TAPS prototype.

Section 5 documents the design and construction of an in-sodium test apparatus for performance evaluation of a Westinghouse TAPS prototype. The test apparatus consists of a mockup test vessel, an Argonne high-temperature acoustic sensor, a TAPS prototype, 10 accelerometers, a signal conditioning module, heating devices, a heating control module, and a data acquisition (DAQ) system. The apparatus is then integrated onto the Argonne under-sodium viewing (USV) facility for both stationary and dynamic tests. This section also describes setup and test conditions of the in-sodium testing of the TAPS prototype. Section 6 discusses the progress and conclusions of the development and demonstration of the TAPS technique for in-situ power/temperature measurement for an SFR. Section 7 provides a future plan for the in-sodium testing of the Westinghouse TAPS prototype. References cited in this report are listed after the future plan.

2 WORKSCOPE

Workscope includes the following four major tasks:

Water mockup test of TAPS prototype

Design and construction of water mockup test apparatus

Argonne will design and construct a water mockup test apparatus for the evaluation of a TAPS prototype that is fabricated by Westinghouse. The test apparatus consists of a mockup test vessel, a hydrophone, an Argonne high-temperature acoustic sensor, a TAPS prototype, an accelerometer, a heating device, a heating controller, and a data acquisition (DAQ) system.

Water mockup test of TAPS prototype

The TAPS prototype will be tested in water at different temperatures (from ambient to 98°C) to determine its performance. The performance evaluation covers the following major subtasks:

- Determine the optimal signal amplification, filtering, and processing conditions;
- Validation and verification of the prototype with a commercial hydrophone and an Argonne high-temperature acoustic sensor;
- Determine the sensitivity, response time, and reproducibility.

In-sodium test of TAPS prototype

Design and construction of in-sodium test apparatus

Argonne will design and construct an in-sodium test apparatus for laboratory pilot testing of the TAPS prototype. The test apparatus will be integrated onto the Argonne under-sodium viewing (USV) facility. It consists of a mockup test vessel, an Argonne high-temperature acoustic sensor, a TAPS prototype, 10 accelerometers, a signal conditioning module, heating devices, a heating control module, and a data acquisition (DAQ) system.

In-sodium test of TAPS prototype

Argonne will conduct an in-sodium test of the Westinghouse TAPS prototype at elevated temperatures under stationary and dynamic modes. The performance evaluation covers the following four major subtasks:

- Determine the optimal signal amplification, filtering, and processing conditions;
- Validation and verification of the prototype with an Argonne high-temperature acoustic sensor;
- Evaluate the flow rate effect;
- Determine the sensitivity, response time, and reproducibility.

3 WORKING PRINCIPLE OF TAPS

This section provides an introduction to the physics of a thermoacoustic power sensor, the design of a TAPS, and the benefits of TAPS technology when applied to nuclear reactors. An array of TAPSs distributed throughout a reactor core is envisioned to provide wireless, real-time measurements of the local coolant temperature and neutron flux conditions as a function of position. A history of the research and development of the TAPS technique and the mathematical description of TAPS basic principles were described in a previous report [1].

3.1 General Description of Working Principles

TAPS technology serves as a mechanism to convert thermal energy to acoustic energy. A TAPS is essentially a thermoacoustic engine that is encapsulated inside an instrumentation tube, i.e. an acoustic resonator. It internally consists of a heat source (hot end), a stack, and an acoustic resonator (cold end), and is usually filled with a noble gas mixture. For consistent heating and better reproducibility, a TAPS is heated by an integral nuclear-powered heater, for example, either a fuel pellet or a gamma-harvesting

material. The use of a passive nuclear-powered heating source eliminates the use of any electric wires and enables the sensor to be wireless, as well as extends the life expectancy of the sensor. Figure 1 shows a schematic of the internal configuration of a TAPS [1]. When heat is introduced to a TAPS at the hot end, the heat is transferred by electromagnetic (EM) radiation to the stack located in between the hot and cold ends of the TAPS. The hollow stack is usually made of ceramics that will better hold and maintain a temperature gradient across the TAPS body. Because of the temperature difference along the stack, larger-scale molecular motion of the filled gas will occur inside the stack between the hot and cold ends, resulting in local gas pressure oscillating between the hot and cold ends and producing thermoacoustic oscillations, i.e. standing thermoacoustic waves.

The standing thermoacoustic waves, traveling back and forth in an acoustic system (path) between the hot and cold ends of the TAPS, ultimately “ring out” at its acoustic natural frequencies. The acoustic waves will then propagate through the reactor coolant (sodium) and through the reactor core structure, and are measured by acoustic receivers located on the outside of the reactor vessel. The wireless-transmitted acoustic signal is then amplified, filtered, and processed by a signal conditioning and data acquisition (DAQ) system. Sound wave amplitude corresponds to the local radiation flux in the core, and the wave frequency is proportional to the local coolant temperature. An array of TAPSs distributed throughout a reactor core is envisioned to provide wireless, real-time measurements of the local coolant temperature and neutron flux conditions as a function of position.

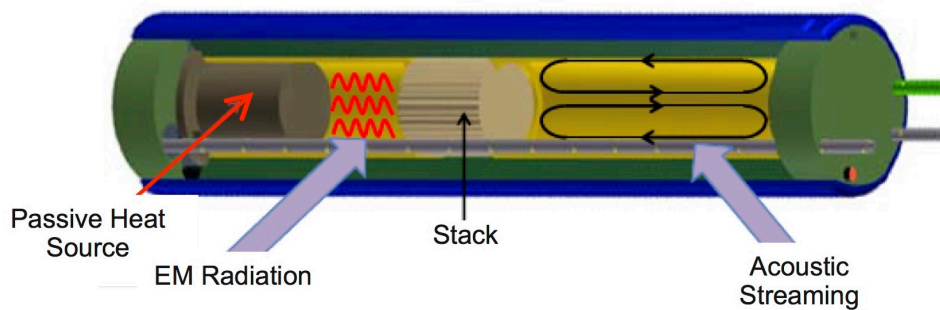


Figure 1. Schematic of the internal configuration of a TAPS [1].

3.2 Design of TAPS Prototype for In-sodium Test

The design specification for a TAPS was driven by the sensor’s application in an SFR environment. In conjunction with exploration of the SFR application, Westinghouse developed a full set of functional requirements for (1) TAPS sensor hardware, (2) TAPS Signal Measurement System (SMS) hardware and software, and (3) the TAPS testing program, which is documented in the Westinghouse internal report RT-FR-15-001 [2]. The Functional Requirements resulted in the development of a TAPS design that was deemed suitable for use in the USV facility at ANL. Based on the mathematical model of thermoacoustic effects [1] and the integrated USV-TAPS test facility at ANL, Westinghouse has designed a TAPS prototype for in-sodium testing in the USV facility. For laboratory pilot testing, the prototype uses an electrical heater to simulate the heating that fuel or a gamma radiation harvester would provide in a commercial TAPS. The housing of the prototype was also modified such that it can be easily installed in or removed from the TAPS test vessel. Figure 2 shows the sketches of the TAPS Assembly design manufactured by Mirion IST. The TAPS design was modified to include the equipment required to interface the TAPS prototype with the penetrations that exist in the sodium test vessel to be used in the sodium small-scale facility at ANL. The manufacturing process details associated with the design are proprietary to the Mirion IST Company, and are not included in this report.

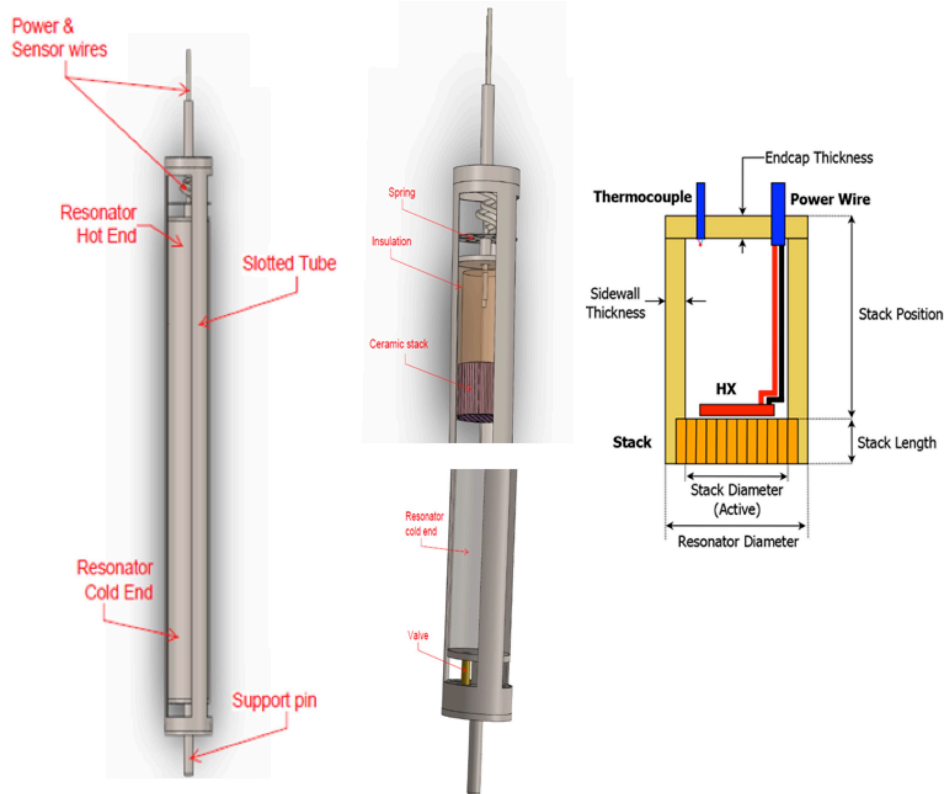


Figure 2. Sketches of the TAPS Assembly design: (left) resonator; (top-right) hot end; (bottom-right) cold end [1].

3.3 Fabrication of TAPS Prototype for In-sodium Testing

Design of TAPS sensor hardware proceeded as an evolution of the 1st generation hardware developed for a synergistic LWR program by Westinghouse, Penn State University, and Idaho National Laboratory (Battelle 00144657). This TAPS design, originally developed for application in water, was modified for the sodium application as discussed below. In addition, the 2nd generation design improvements included a thermal core with improved efficiency and simpler, more robust fabrication methods. Figure 3 shows a TAPS prototype manufactured by Mirion IST for in-sodium performance evaluation.

Generating thermoacoustic sound requires a large steady-state temperature gradient across the stack. Therefore, a major effort was focused on designing a TAPS that has an improved “thermal core” with optimal electrical heater, insulation, and stack structures. A typical thermoacoustic engine has a diameter on the order of several inches, which simplifies the placement of electrical heaters, insulation, and the armored passthroughs necessary to connect electrical power and feedback devices such as thermocouples. Miniaturizing such a system to the sub-inch diameter of the TAPS prototype represents significant design and fabrication challenges. The detailed design and fabrication of the TAPS prototype were documented in Ref. 1.



Figure 3. TAPS prototype for in-sodium performance evaluation.

The prototype, shown in Figure 2 and 3, consists of the following main components:

- **Slotted tubing:** The tubing is used to support and protect the TAPS. It is made of 316L stainless steel (SS-316L), which meets chemical compatibility requirements. A positioning pin is welded at the bottom end of the tubing to keep the TAPS in place inside the test vessel.
- **TAPS shell:** The shell is an acoustic resonator made of SS-316L, which meets chemical compatibility requirements. The housing is leak tested and filled with the pressurized noble gas, which minimizes the oxidation of the electric heater and extends its service life. The sound speed of the gas determines the frequency of a resonator, and the thermos-viscous properties of the gas influence the efficiency of thermoacoustic energy conversion. A mixture of 80% helium and 20% argon was selected to achieve the desired frequency range. A SS tubing is welded at the hot end of the shell and is fed through and tap-welded with the slotted tubing. The electric wire of the electric heater is then fed through the tubing.
- **Electrical heater:** To simulate the heating that fuel or a gamma radiation harvester would provide in a commercial TAPS, an electric heater is used. It is a 26-gauge round wire made of NICHROME 80 alloy. Table 1 shows the heater specifications. This heater is chosen for its high temperature tolerance and minimal oxidation with the working gases. Figure 5 shows the configuration of the electric heater designed by Mirion IST.
- **Stack:** The stack is made of a ceramic block that has a structure with small, contiguous, longitudinal channels through which gas mixture (acoustic waves) can flow. Figure 4 shows a picture of the ceramic stack. Its regularity and temperature tolerance also meet the design requirements of the TAPS to be tested in sodium. A temperature gradient is enforced between the hot and cold ends to initiate thermoacoustic conversion of thermal energy into acoustic waves.
- **Insulation cap:** The cap has a structure that helps to enforce the required temperature gradient across the stack.
- **Isolation springs:** The springs, mounted at the top and bottom respectively inside the tubing in between the tubing and shell, allow the TAPS shell to move with the internally-generated thermoacoustic sound and transmit sound through the coolant (e.g. sodium) surrounding the TAPS.
- **Holding assembly:** The assembly is used to hold and keep the TAPS in place as well as to protect the electric wire of the electric heater feeding through it from the coolant (sodium). It consists of a bellows and a holding tubing. The bellows has one end connected to the tubing of the TAPS shell and another end to the holding tubing using Swagelok® fittings. The bellows is added to allow thermal extension of the TAPS prototype while the prototype and the coolant are heated up. To avoid coolant leaks into the assembly, all the fittings were removed and all the connections were welded together.
- **Thermocouple:** A K-type thermocouple is inserted into the hot-end of the TAPS prototype to monitor the temperature of the electric heater.

Table 1: Specifications of NICHROME 80 alloy

Diameter	26 Gauge / 0.4039 mm
Shape	Round
Composition	80% Ni, 19.5% Cr, 1.45% Si
Heat Treatment	Annealed (soft)
Melting Temperature	1,400°C (2,552°F)
Max Operating Temperature	1,180°C (2,150°F)
Resistance	2.5711 Ohms/ft. at room temperature

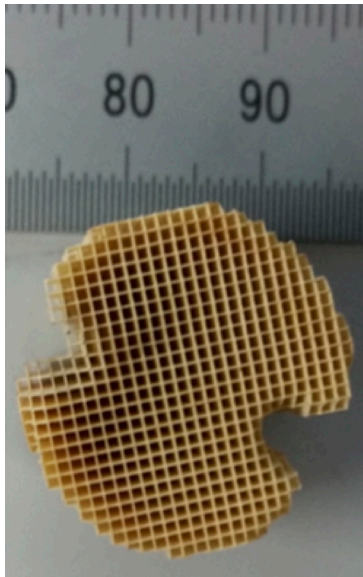


Figure 4. Top view of ceramic stack, with scale [1].

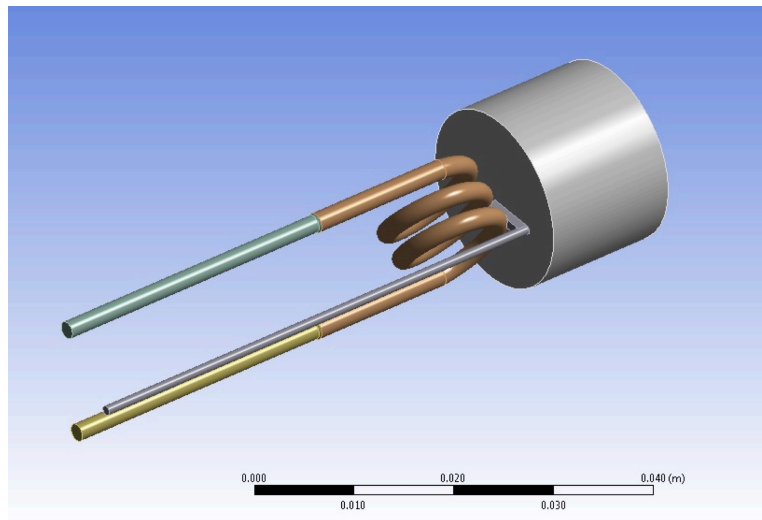


Figure 5. Configuration of electric heater designed by Mirion IST [1].

4 WATER MOCKUP TEST OF TAPS PROTOTYPE

Before being tested in sodium, the TAPS prototype needs to be tested in water to verify if the prototype is still functioning properly after shipping. The water mockup test allows us to test the instrumentation setup and the DAQ system of TAPS in-sodium test. This section documents the construction of a water mockup test apparatus, and then reports the results of water mockup tests of the TAPS prototype.

4.1 Water Mockup Test Apparatus

Argonne constructed a test apparatus for water mockup testing of the TAPS prototype. Figure 6 shows a picture and dimensions of the TAPS prototype after the Swagelok fittings were removed and all of the connections were replaced with welding. The test apparatus consists of a mockup test vessel, a hydrophone, an Argonne high-temperature acoustic sensor, a TAPS prototype, a charge accelerometer, a heating device, a heating controller, and a data acquisition (DAQ) system. Table 2 lists the instrumentation of the water mockup test.

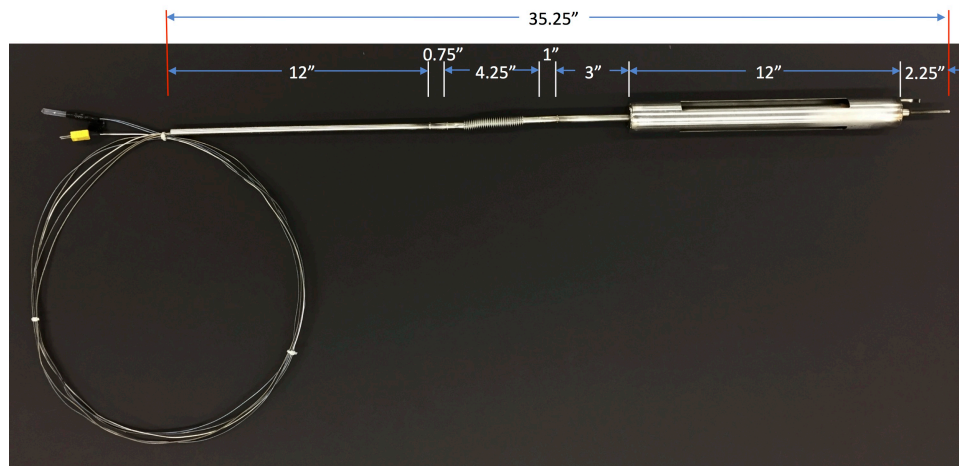


Figure 6. Picture of a TAPS prototype.

Table 2: Instrumentation List of Water Mockup Test

Name	Model	Specifications
Charge Accelerometer	PCB 357B61	10 pC/g, T_{\max} : 482°C/900°F, 5 KHz
In-line Charge Converter	PCB 422E36	10 mV/pC, ± 2.5 V, 121°C/250°F
Charge Amplifier	PCB MOD 462A	
Dual Filter	DL 4302	Dual 24 dB/octave, 10 Hz – 1 MHz
Sensor Signal Conditioner	PCB 483C41	8 Channels, Sensor: ICP®, Charge, Voltage
Eight-Slot USB Chassis	NI cDAQ 9178	0 – 10 MHz
Analog Input Module	NI 9215	4 AI, ± 10 V, 16 Bit, 100 kS/s/ch Simultaneous
Thermocouple Module	NI 9213	16 TC, ± 78 mV, 24 Bit, 75 S/s Aggregate
DC Power Supply	VOL TEQ HY3005D-3	Dual Channels, 0 – 30 VDC, 0 – 5 A

The test vessel is filled with distilled water and a heating tape is wrapped around its outer wall. The temperature is controlled by a Variac and monitored by a K-type thermocouple device. The TAPS prototype is placed at the center of the vessel and a hydrophone and an Argonne high-temperature acoustic

sensor is submerged in water away from the prototype. A high-temperature charge accelerometer is mounted on the outer wall of the vessel using a high-temperature adhesive. The received signals of the three different receivers (accelerometer, hydrophone, and acoustic sensor) are amplified by charge amplifiers, and then filtered by gain amplifiers, respectively. An 8-channel analog input module then digitizes the processed analog signals. The digitized signals are transferred to a DAQ system, which runs on an NI LabView platform. Through application of Fast Fourier Transform (FFT), the DAQ system converts the received acoustic signals to frequency spectra, respectively. The amplitude and natural frequency of the acoustic sound then can be obtained. The output of the hydrophone is mainly used for the verification of the outputs of the acoustic sensor and the TAPS prototype at ambient temperature. Figure 7 shows the water mockup test apparatus before the installation and insulation of the heating element onto the water vessel. Sound wave amplitude corresponds to the local radiation flux in the core, and the wave frequency is proportional to the local coolant temperature.

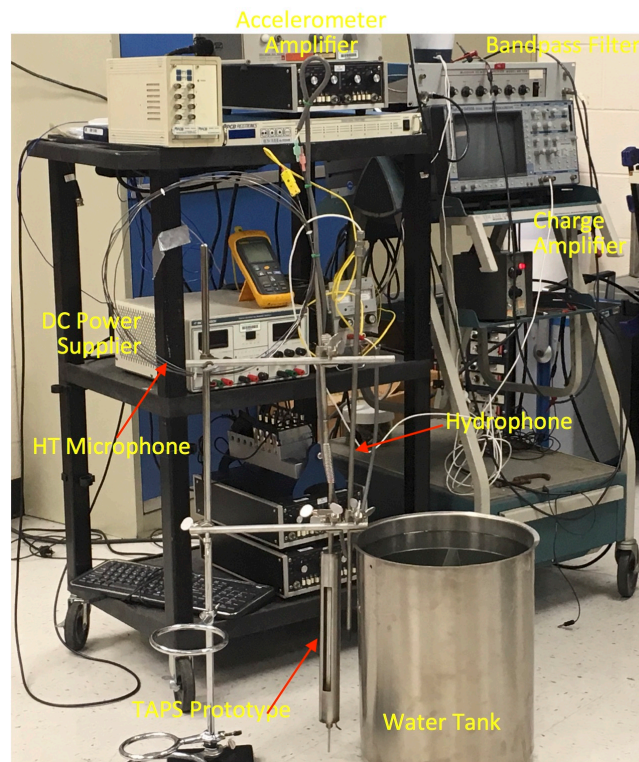


Figure 7. Water mockup test apparatus before heating element installation.

4.2 Instrumentation and Control System

An instrumentation and control (I&C) system was developed to operate both the water mockup test and the in-sodium test facility. The system consists of three major modules: USV-TAPS, DAQ, and control and display (C&D). The functionalities of the three modules are described as the following:

- **USV-TAPS module:** This module consists of the USV sodium loop and the TAPS test apparatus. There are two test modes: stationary and dynamic. The TAPS apparatus is isolated from the USV sodium loop when tested under stationary mode. During an in-sodium test under dynamic mode, molten sodium (at 200°C) is circulated through the USV-TAPS sodium loop by an EM pump. This module controls and monitors the temperatures of sodium in the TAPS test vessel and the TAPS

electric heater. It also monitors the sodium flow rate of the EM flowmeter of the USV sodium loop during an in-sodium test under dynamic mode.

- **DAQ module:** This model consists of analog-to-digital converting units and a DAQ computer. Three types of receiver (TAPS prototype, hydrophone, and acoustic sensor) are used for water mockup tests. The analog signals are measured, amplified, and filtered before feeding to analog-to-digital converting units (NI 9215). The temperatures of the TAPS probe and the sodium within the test vessel are also measured by K-type thermocouples, respectively, and digitized by a TC unit (NI 9213). The USB chassis unit (NI cDAQ 9178) then transfers the digitized acoustic signals and temperatures to the DAQ computer, which processes and analyzes the received acoustic signals, and then to get the acoustic amplitude and resonance frequency the TAPS probe at the operating (sodium) temperature.
- **Control and Display (C&D) module:** This module controls and displays the operating parameters of the NI units used in the DAQ module, and then displays results on the DAQ computer. Figure 8 shows the control and display (C&D) panel of the I&C system running on the LabView[®] platform. The top-left of the panel shows the DAQ control of the NI units and their operating parameters; top-right shows the temperatures of sodium in the test vessel and electric heater of the TAPS probe; bottom-left shows the spectrum of the acoustic signal of the three receivers respectively by switching the inputs; and bottom-right shows the spectrogram of the three receivers respectively by switching the inputs.

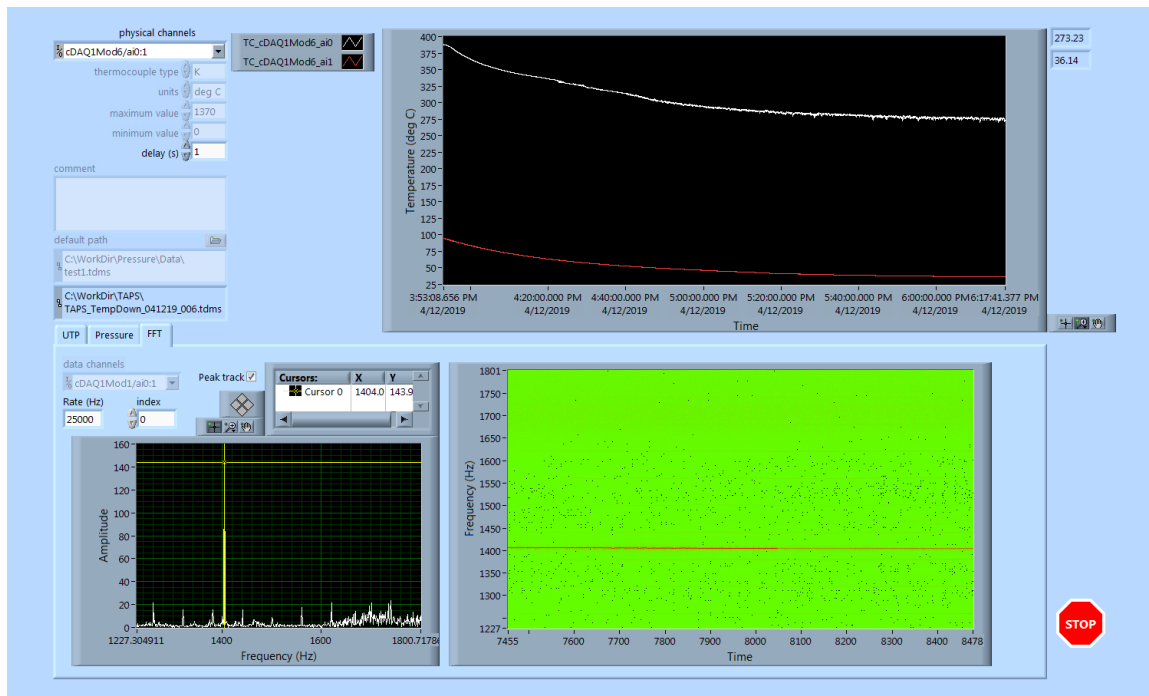


Figure 8. Control and display (C&D) panel of the TAPS I&C system: (top-left) DAQ control; (top-right) temperatures; (bottom-left) spectrum; (bottom-right) spectrogram.

4.3 Water Mockup Test of TAPS Prototype

All the components or sensors used and submerged in sodium usually require some kind of water mockup testing to verify their functionalities, mechanisms, operation, or sodium capability. Thus, before in-sodium testing, water mockup tests of the TAPS prototype were conducted 1) to validate if the prototype is

functioning properly, 2) to optimize operation and signal conditioning, and 3) to assist the development of a control and DAQ system. To reduce dissolved gas and minimize the attenuation of the acoustic signal, the test vessel is filled with distilled water. A fiberglass trace heater is wrapped around its outer wall and the water temperature is controlled by a Variac transformer and monitored by a K-type thermocouple. The TAPS prototype is placed at the center of the vessel and a hydrophone and an Argonne high-temperature acoustic sensor are submerged in water away from the prototype. A high-temperature charge accelerometer is mounted on the external wall of the vessel using a high-temperature adhesive. The received signals of the three different receivers (accelerometer, hydrophone, and acoustic sensor) are amplified by charge amplifiers, and then filtered by gain amplifiers, respectively. The conditioned analog signals are digitized by an 8-channel analog-to-digital (A/D) module. The digitized signals are then transferred to a DAQ system, which runs on an NI LabView platform. Through Fast Fourier Transform (FFT) processing, the DAQ system converts the received acoustic signals to frequency spectra, respectively. The amplitude and natural frequency of the acoustic sound then can be obtained. Sound wave amplitude corresponds to the local radiation flux in the core, and the wave frequency is proportional to the local coolant temperature. The output of the hydrophone is mainly used for the verification of the outputs of the acoustic sensor and the TAPS prototype at ambient temperature. Figure 7 shows the water mockup test apparatus before the installation and insulation of heating elements onto the water vessel.

An instrumentation and control (I&C) system, running on the NI LabView platform, was developed to operate both the water mockup test and the in-sodium test facility. The system is able to select and control different inputs from different NI DAQ modules, acquire digitized signals, process and analyze the signals, and display the control parameters and results (temperatures, spectra, and spectrogram). The prototype was successfully tested in a water bath with temperature ascending or descending continuously between ambient to 97°C. Water mockup tests demonstrated that the TAPS prototype is working properly and its resonance frequency changes linearly with the coolant (water) temperature. Figure 9 shows spectrum of the TAPS prototype at water temperatures of 37.39°C and 95.97°C, respectively, and the corresponding resonance frequencies of the TAPS prototype are 1,408.1 Hz and 1,527.5 Hz.

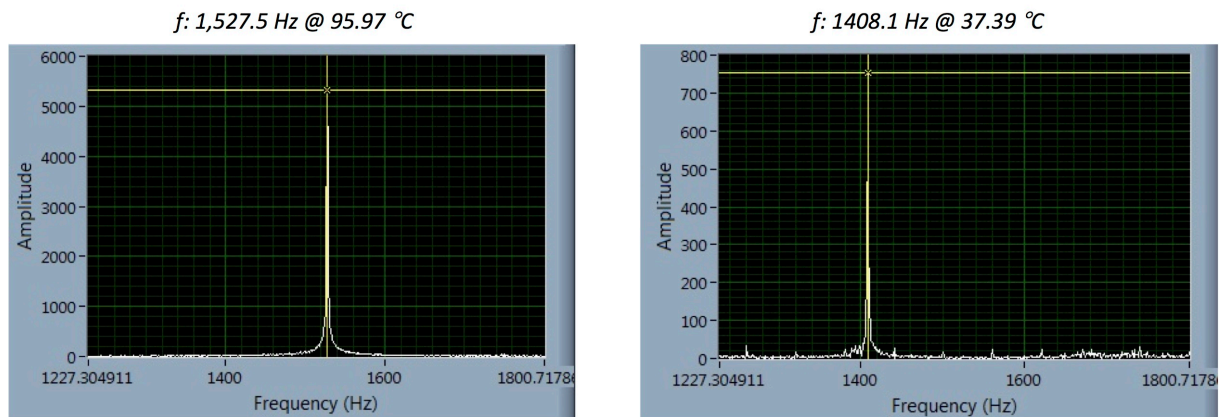


Figure 9. Spectrum of TAPS at water temperature of (left) 95.97°C and (right) 37.39°C.

Figure 10 shows the comparison of the resonance frequencies measured by an Argonne high-temperature acoustic sensor and a charge accelerometer at different water temperatures. It verifies that the TAPS prototype is functioning properly. It also validates that the resonance frequency of the TAPS prototype is linearly proportion to the water (coolant) temperature. The measurements of the two sensors are almost identical and both can be used for core power/temperature monitoring within or from outside of the core. Figure 11 shows the resonance frequencies of the TAPS prototype measured by a charge accelerometer with water temperature ascending from 29°C to 97°C. Figure 12 shows the resonance frequencies of the

TAPS prototype measured by a charge accelerometer with water temperature descending from 97°C to 29°C.

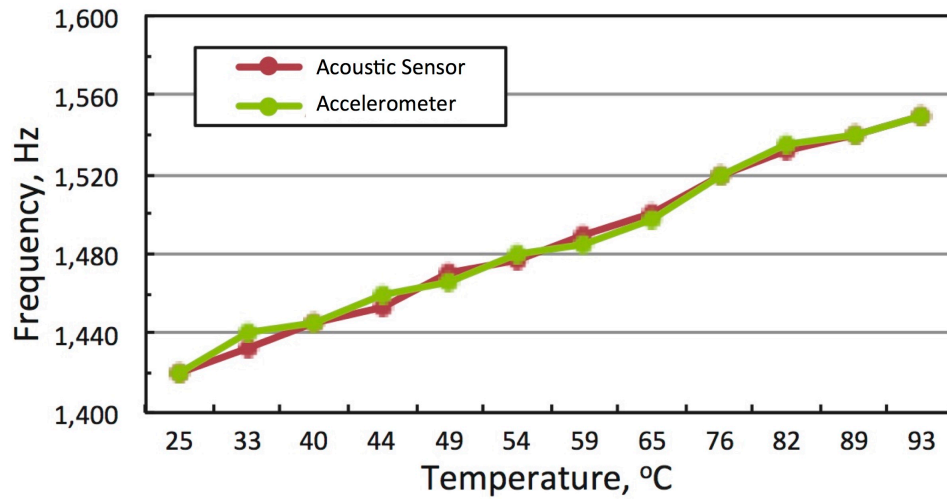


Figure 10. Resonance frequencies measured by acoustic sensor and accelerometer at different water temperatures.

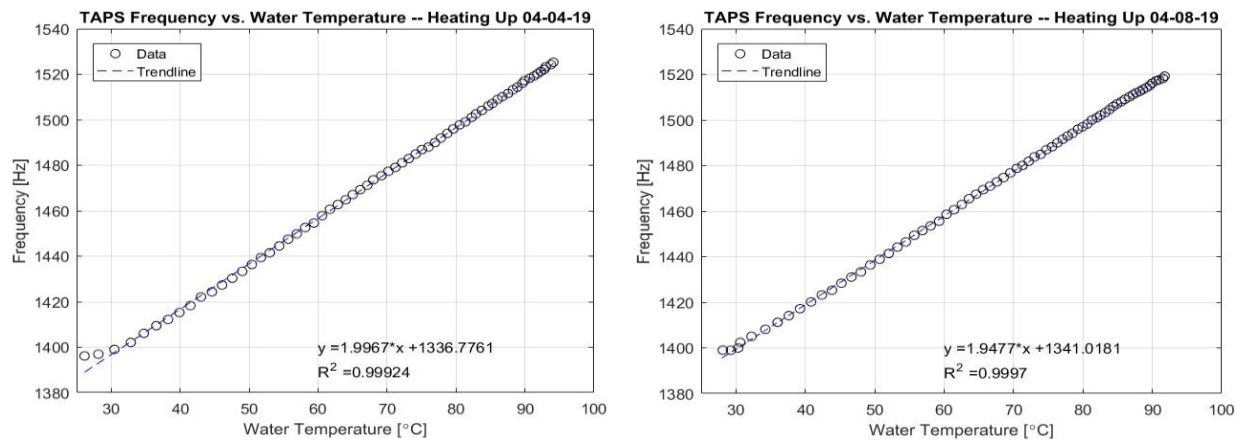


Figure 11. Resonance frequency of TAPS prototype with water temperature ascending.

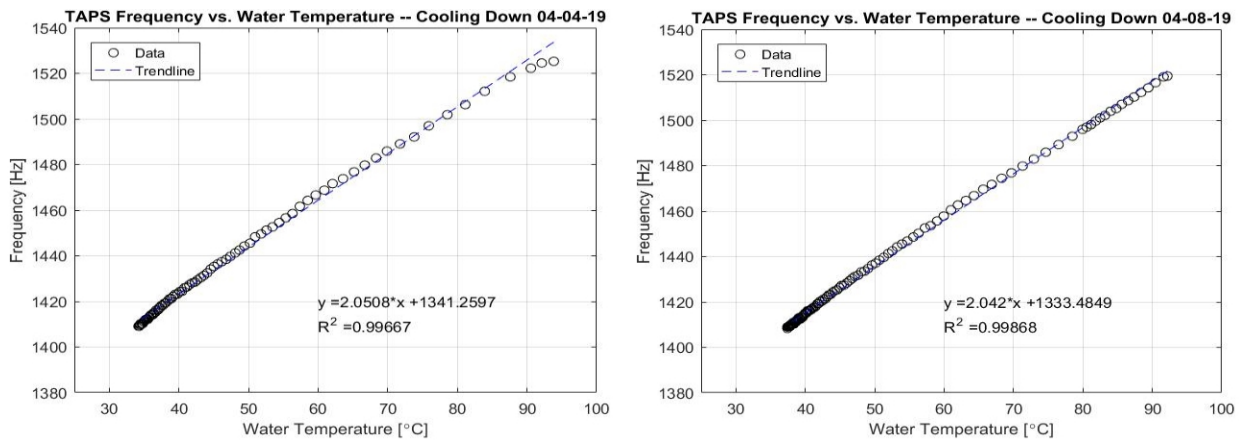


Figure 12. Resonance frequency of TAPS prototype at water temperature descending.

5 IN-SODIUM TEST of TAPS Prototype

The TAPS, developed by Westinghouse, potentially could be used for real-time core temperature/power monitoring of an SFR. The objective of this project was to develop and demonstrate the TAPS technique in a sodium environment. Argonne has developed a USV sodium test facility for the development and demonstration of an ultrasonic under-sodium viewing technique for the detection of component defects or the monitoring of operation within an SFR core. This small-scale sodium facility can be also used to investigate the effect of sodium on in-core sensors and their performance. This section documents the construction and integration of the TAPS test apparatus and the USV test facility for in-sodium testing of a TAPS prototype. The in-sodium testing of a TAPS prototype is currently delayed due to design changes, construction issues, and the required formal safety review of the integrated USV-TAPS sodium test facility.

5.1 Integration of USV Sodium Test Facility and TAPS Test Apparatus

The Argonne USV sodium test facility was developed for the demonstration of an ultrasonic under-sodium viewing technique for the detection of component defects or the monitoring of operation within an SFR core. Two new sensors, TAPS and in-sodium hydrogen meter (ISHM), are being developed and needed to be tested in sodium. The USV facility needed to be modified to accommodate these two new test apparatuses. These three test apparatuses also need to be able to be operated independently, if necessary. To achieve independent operation, the TAPS and ISHM test apparatuses are branched from the USV sodium loop. Figure 13 shows a diagram of the TAPS test apparatus that is integrated onto the USV sodium test facility and parallels to the ISHM test apparatus. Each apparatus has two high-temperature valves for sodium input and output that are used to isolate the apparatus from the USV sodium loop. A TAPS test may be operated either in stationary or dynamic mode. While running in stationary mode, the TAPS test vessel is isolated from the USV sodium loop by closing the isolation inlet and outlet valves. When running in dynamic mode, these two valves will be opened and the sodium circulation is then controlled by the EM Pump Control Unit of the USV sodium test facility. The detailed design and operating procedures are documented in Argonne Work Control Documents.

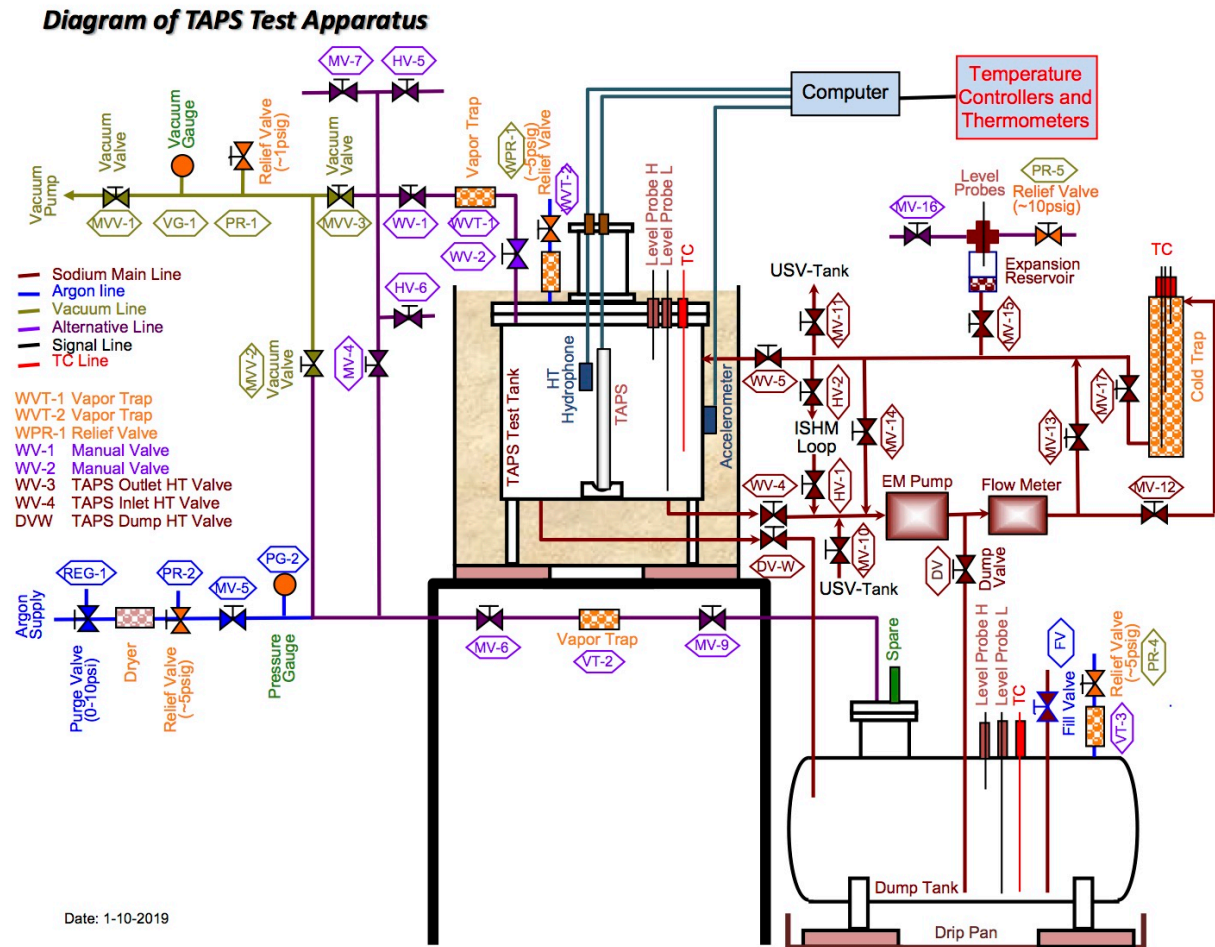


Figure 13. Diagram of sodium small-scale facility for in-sodium test of TAPS prototype.

To accommodate additional sodium needed for the TAPS and ISHM test apparatuses, the original dump tank (15 gallons) of the USV facility was replaced with a larger one (35 gallons). Figure 14 shows the design of the new dump tank that is certified and ASME Code stamped. Feedthroughs on the top of the tank body allow access for sodium transport lines, thermocouples, level probes, and instruments. Figure 15 shows the new dump tank that is constructed with a SS pipe of 16" in diameter and 34" in body length with 2:1 ellipsoidal heads welded at each end. It is wrapped with three trace heaters for separated heating zones. One level probe is set at one inch from the tank bottom, the other is at the high-level point (11.2 inches, 70% tank inner height) for sodium filling. The level sensors are simple conductivity sensors that measure the resistance between the sensor and electric ground. When the sensor wire is in contact with sodium, low resistance will be measured indicating that the desired sodium level has been reached. A K-type thermocouple is installed to monitor sodium temperature. The whole system is leak-tested to hard vacuum. One sodium transport line of the dump tank is directly connected to one of the sodium transport lines (called 'dump line') at the bottom of the TAPS test vessel for fast feeding and dumping without flowing through the USV sodium loop. The other is connected to the USV sodium loop as well as used for a sodium filling line. A pressure gauge and a pressure relief valve are mounted on a sodium cold trap connected to the cover gas/vacuum line for monitoring the argon cover gas pressure.

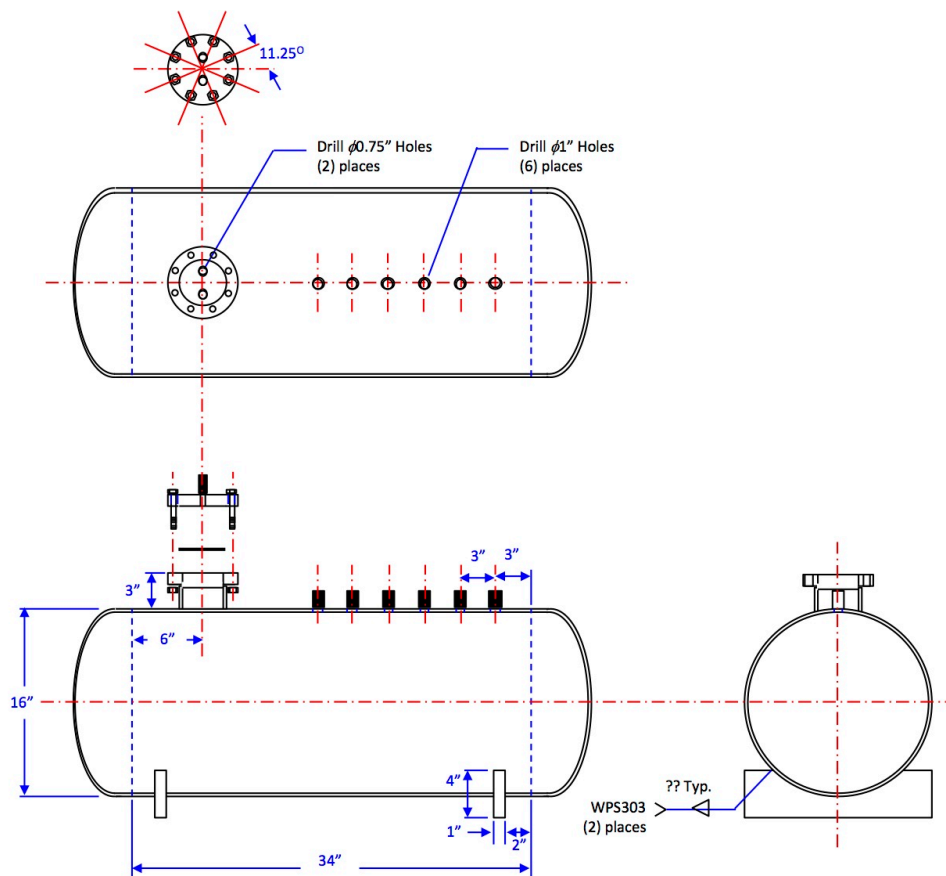


Figure 14. Design of the new dump tank of the USV sodium test facility.

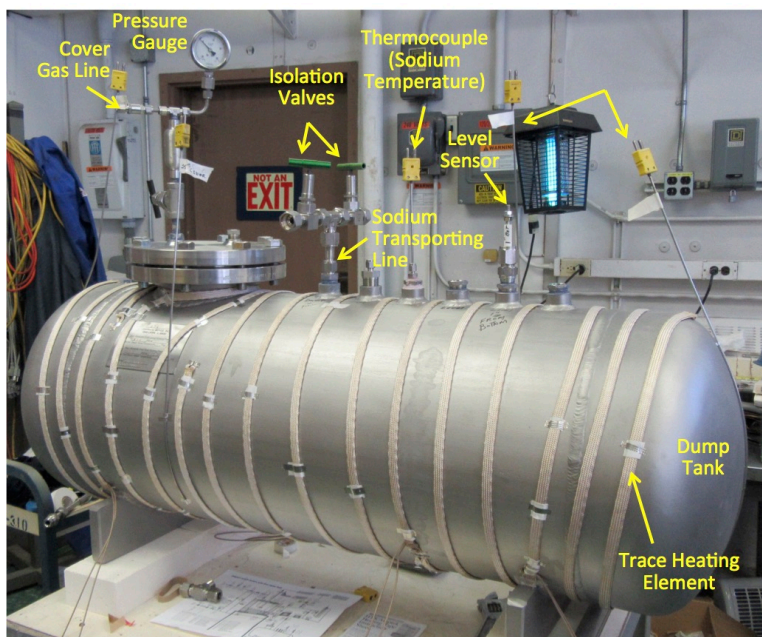


Figure 15. New dump tank of the USV sodium test facility.

5.2 Test Apparatus for In-sodium TAPS Test

To investigate the effects of sodium on an in-core TAPS prototype and its performance, an in-sodium test apparatus has been designed and constructed. The TAPS test apparatus is integrated, parallel to the ISHM test apparatus, onto the USV sodium test facility. Figure 16 shows the layout of the small-scale (USV-TAPS-ISHM) sodium test facility. The TAPS test apparatus consists of a test vessel and a sodium loop. TAPS tests could be operated in either stationary or dynamic mode. Through two shut-off valves, the TAPS test apparatus can be isolated from the USV sodium loop for service or for a test under stationary mode. The resonance frequency of the TAPS shifts linearly with the temperature change of the coolant (sodium) in the nuclear reactor core, which can be correlated to the reactor's power change. An array of accelerometers and a sodium-submersible high-temperature acoustic sensor will be used to measure the acoustic resonance generated by the TAPS prototype. The installation of thermal insulation on the facility is in progress.

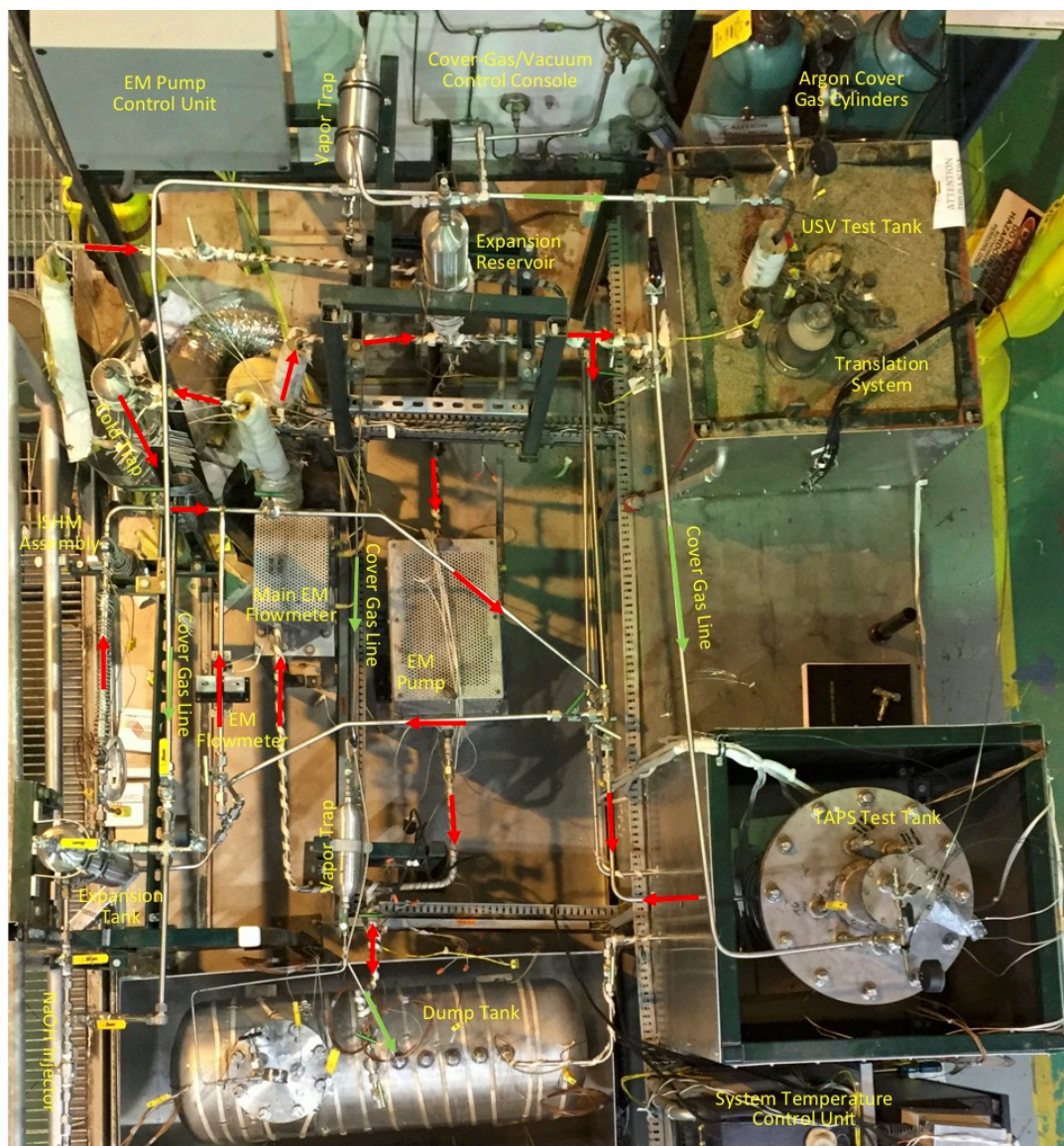


Figure 16. Layout of USV-TAPS-ISHM sodium test facility.

Test vessel Configuration

Two identical TAPS test vessels, one for water mockup at Westinghouse and the other for in-sodium testing of TAPS prototype at Argonne, have been fabricated. The TAPS test vessel, as shown in Figure 17, was built from an 12", schedule 40, stainless steel 304 (SS 304) pipe to which a slip-fit flange (class 300) is welded internally on top and a 304-SS flat plate of ¼" in thickness is welded on bottom. The 19.5" tall vessel was built and tested according to ASME Code Section VIII and is ASME Code stamped.

The operating specifications of the TAPS test vessel are:

- Maximum temperature = 343°C (650°F)
- Sodium loop temperature: 200°C (392°F)
- Cover gas pressure: 3 psi – 5 psi
- Maximum sodium volume of TAPS test vessel: 25.04 liters (6.62 gallons).



Figure 17. TAPS test vessel for in-sodium testing of TAPS prototype.

The TAPS test vessel consists of three sodium pipelines: a sodium inlet at the half height of the vessel for sodium circulating for testing under dynamic mode, an outlet at the vessel bottom for sodium circulating for testing under dynamic mode or sodium cleanup, and a filling/dumping pipeline at the vessel bottom for simple and fast sodium filling or dumping without circulation through the USV sodium loop. Each pipeline has an isolation valve installed to isolate the test apparatus from the USV sodium loop or the dump tank. The pipelines of the apparatus are made of SS tubes 0.5" in diameter.

The top flange assembly of the TAPS test vessel, shown in Figure 18, consists of three parts: a cover flange, an extension cap, and a cap cover flange. The assembly was also constructed under the same ASME specification. The cover flange is 19" in diameter with a 4" hole in the middle and six ¾" half couplings welded onto it for sodium level probes, TC, relief valve, and cover gas/vacuum line, which connect to a pressure gauge for monitoring the argon cover gas pressure. The layout of sodium and gas/vacuum lines is shown in Figure 13. The three level sensors fed through the cover flange are set for low, fill, and high. The

low-level sensor is an indicator that the vessel is emptied during sodium dumping; the fill-level sensor is an indicator that the sodium reached the designed level for in-sodium testing, the high-level sensor is a warning that the sodium level reaches the maximum height allowed. The level sensor, sealed by a graphite compression seal, is simply a conductive wire welded on the tip of a spark plug that measures the resistance between the sensor and the ground. When the sensor wire is in contact with sodium, low resistance will be measured indicating that the desired sodium level has been reached. A K-type TC is installed to monitor sodium temperature.

The extension cap (a pipe of 4" in diameter and 10" in height) allows the TAPS resonator to be lifted out of the liquid sodium and removed from the test vessel without sodium dumping of the vessel, nor opening the cover flange that might cause sodium contamination. One end of the cap has a 4.5" flange welded on it for mounting on the top cover flange. The other end has a 4" plate, consisting a 1" insertion hole, welded on it. The 4" cap cover flange consists of two ½" half couplings welded on it for the TAPS and accelerometer. The TAPS prototype will be inserted into the sodium through an inserting port at the center of the cap cover flange. An acoustic sensor will be inserted into sodium through a feedthrough at the top of the flange.

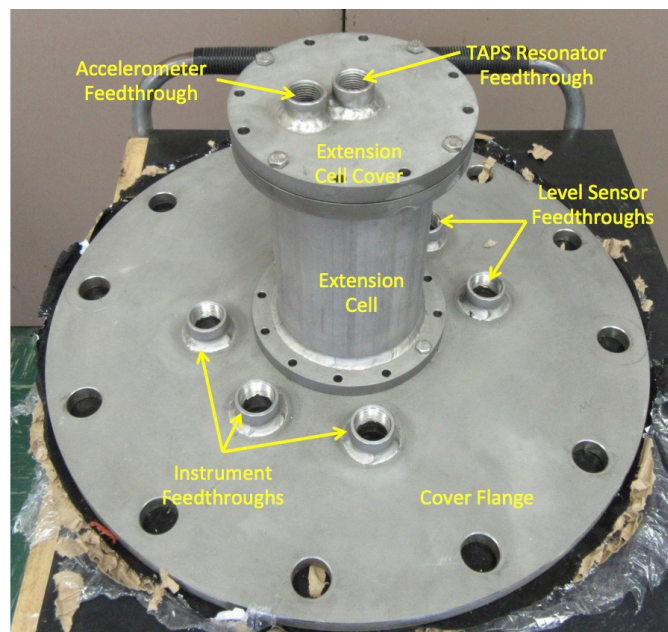


Figure 18. Cover flange assembly for the test vessel to be used for in-sodium testing of TAPS resonator in sodium small-scale facility.

Optimal Mounting Locations of Sensors

An array of accelerometers is mounted on the external wall of the vessel body, bottom, and top flange to measure the acoustic resonance generated by the TAPS prototype. A sodium-submersible high-temperature acoustic sensor developed at Argonne, inserted into the sodium through a feedthrough on the top flange, will also be tested simultaneously. There is a concern that the distinct structural-acoustic modes of the test vessel would be close to the operating frequency range of the TAPS prototype (around 1-2 kHz). If a vibrational mode coincided with the TAPS frequency range, unanticipated amplification or attenuation of the TAPS signals could give wrong readings of the coolant (sodium) temperature. The mounting locations of the accelerometers might be critical for optimal signal reception or sensor sensitivity. To minimize the probability of such a modal effect, the geometry of various vessel components (e.g. sidewall, top flange,

base, etc.) were designed to minimize modal influences in this range. The modal analysis would also assist with the determination of the optimal mounting locations of the accelerometers. The University of Pittsburg conducted modal analysis based on the test vessel design and the operating frequency range of the TAPS prototype. Figure 19 shows the selected mounting locations of the 10 accelerometers on the tank wall, tank bottom plate, and the cover flange. Since being submerged into sodium and sodium has very good acoustic properties, the location of the acoustic sensor is not so critical as that of the accelerometers as long as it is not too close to the TAPS prototype. However, it might take some time for the acoustic sensor to get optimal receiving signal because of sodium wetting of the sensor. The wetting process could be speeded up, if the sodium temperature is high and the sodium is flowing.

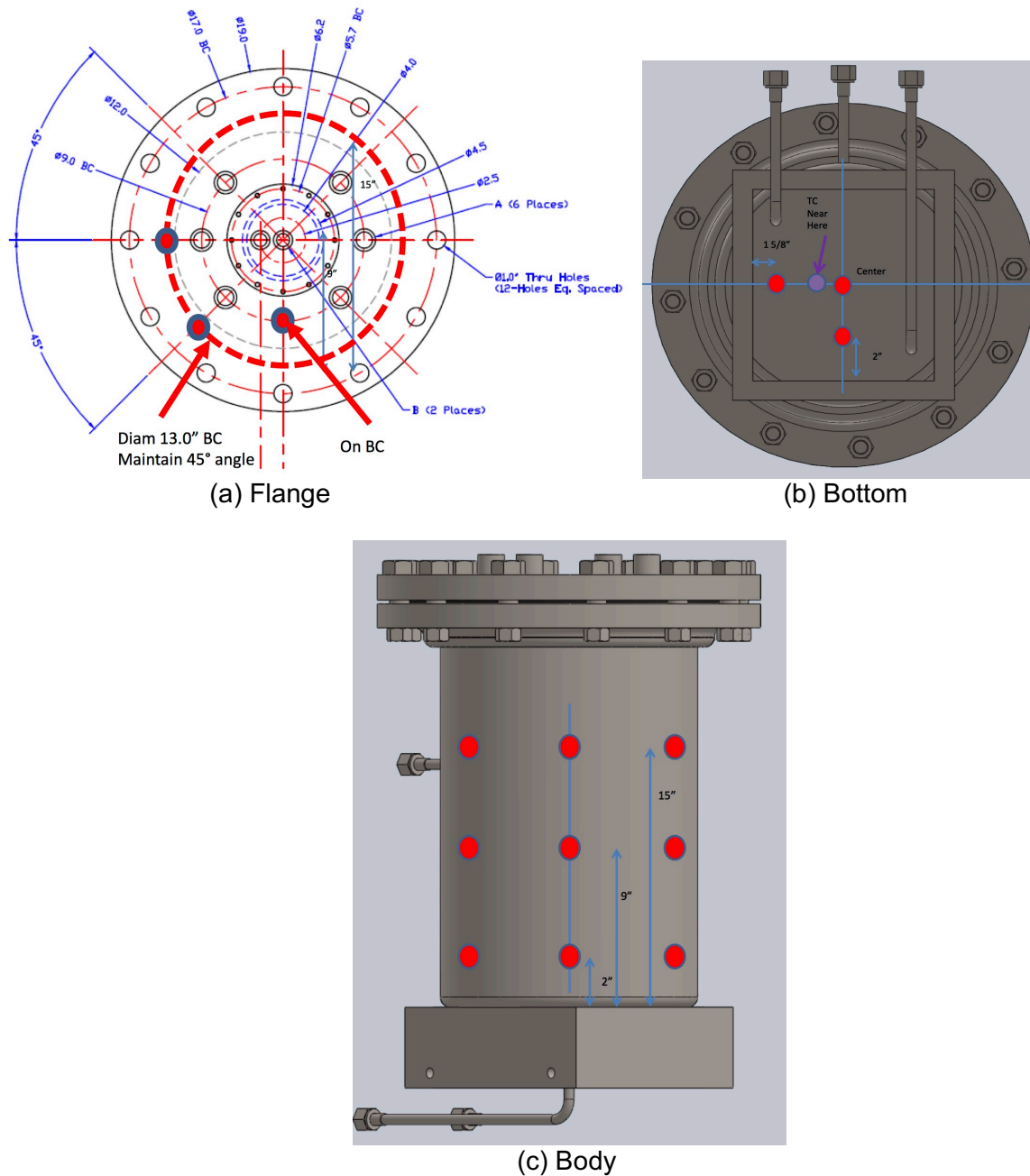


Figure 19. Accelerometer mounting locations.

Bonding Material and Mounting Base:

To monitor the frequency and intensity of the TAPS resonator, accelerometers, mounted on mounting bases, will be bonded on either the bottom or the wall of the test vessel, or on the flange. A high-temperature bonding material was recommended to install the mounting base, made of aluminum, on the test vessel wall. Due to the different thermal expansion coefficients between stainless steel wall, bonding material, and the aluminum mounting base, bonding strength evaluation of the bonding materials was conducted to ensure that the mounting base would bound on the vessel without failure due to high temperature and thermal cycling between room temperature to 650°F. A stainless-steel blind extension cell cover flange was used to simulate the vessel instead. Aluminum mounting bases were mounted on the cell cover using different bonding materials, respectively, then placed in a furnace with temperature cycling between ambient and 650°F. Unfortunately, none of the bonding approaches survived more than two cycles. Figure 20 shows a failed mounting base and a mounting base bonded on the blind flange for the extension cell. The issue of mismatch of thermal expansion rate might be resolved by using the same material for both of the vessel and mounting base. A dozen stainless steel mounting bases were fabricated. Figure 21 shows one of the stainless-steel mounting bases that were used for thermal cycling testing. The same bonding material was used for strength evaluation, i.e. the same thermal cycling test. Unfortunately, while the bonding survived more cycles, it too failed. A different bonding material was then selected and tested successfully without any failures.

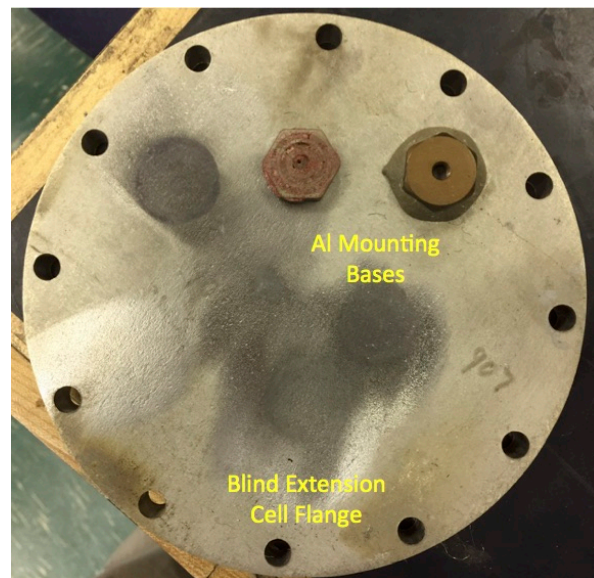


Figure 20. Picture of (left) a failed mounting base and (right) a mounting base bonded on the blind flange.

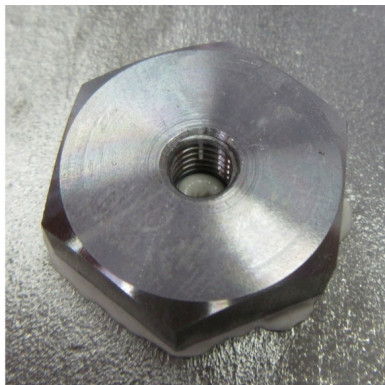


Figure 21. Picture of a new stainless-steel mounting base

Construction and Integration of TAPS Test Apparatus

The TAPS experiment apparatus is integrated into the sodium test facility. It is located in the Building 308 High-Bay at Argonne. An array of accelerometers was mounted at the locations resulting from the modal analysis. The TAPS test vessel was then placed in a SS secondary container (28.5W"x30D"x30.5H"). VCR fittings are used between all the connections that would be in contact with molten sodium. All the valves that would be in contact with molten sodium are bellows-sealed valves welded with VCR fitting end connections supplied by Swagelok (SS-8UW-V47) of 480 psig @1,000°F (537°C). Unplated nickel gaskets (NI-8-VCR-2-VS or NI-8-VCR-2-GR-VS) are used for all the VCR fitting connections supplied by Swagelok. Fiberglass trace heaters (HTS/Amptek, up to 900°F) are mounted on the outer walls of the vessel body and all the pipelines and valves. A temperature control unit was constructed to control and monitor the temperatures of the test vessel and pipelines are controlled. Figure 22 shows a picture of the test vessel configured with heating elements and accelerometers inside the secondary container.



Figure 22. Test vessel configured with accelerometers and heating elements.

A TAPS prototype was installed into the test vessel through the center feedthrough on the cover cap flange. Figure 23 shows the setup of a TAPS prototype inside the test vessel. Level sensors, TCs, acoustic sensor, accelerometers, and instruments have also been installed (Figure 24). The test vessel was sealed and all the pipelines are connected. The assembly of the TAPS test apparatus and the modification of the USV sodium test facility have been completed and integrated together (see Figure 17). The integrated USV-TAPS sodium test facility was leak-tested to hard vacuum. The insulation of the facility was completed. The test apparatus is currently at a standby condition and is purged with argon cover gas at a pressure slightly higher than the ambient (~ 2 psig). Before transferring sodium, the secondary containment will be filled with vermiculite for thermal and electric insulation. Vermiculite is a fire-resistant material that can minimize a possible fire, if there is a sodium leak. It is also removed easily by using a vacuum machine, if servicing of the apparatus is needed. Sodium will be transferred into the vessel for in-sodium testing once the facility is formally approved for operation.

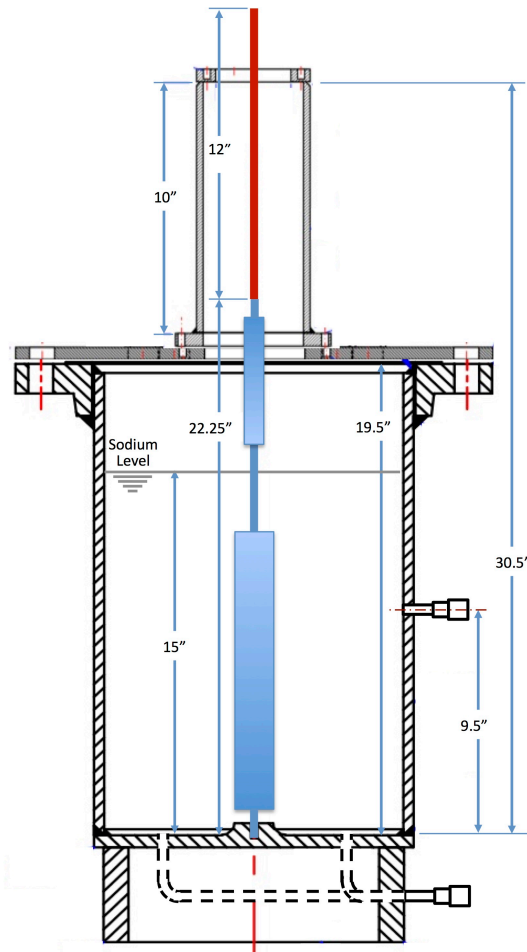


Figure 23. Diagram of TAPS Test Setup.

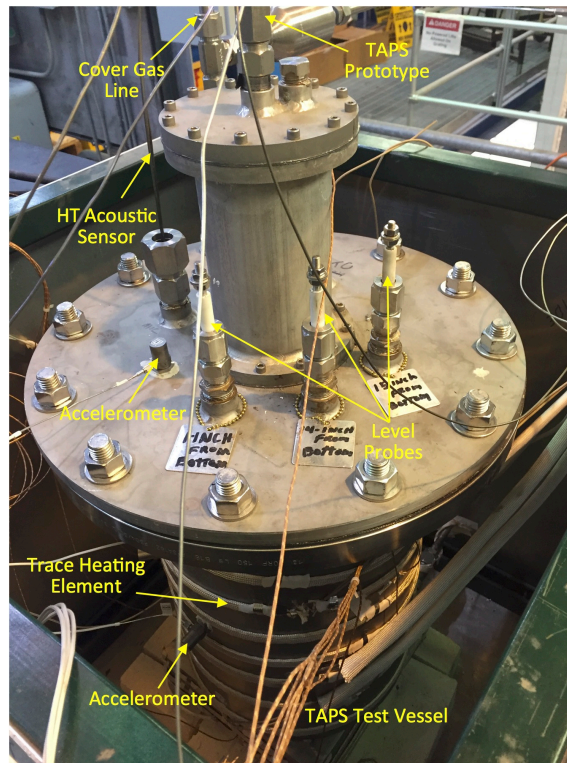


Figure 24. Picture of TAPS Test Setup.

The TAPS prototype and the acoustic sensor were both tested after they were inserted into the test vessel and after leak testing of the vessel. Figure 25 shows the spectrogram of the prototype inside the test vessel under ambient condition. The preliminary tests have demonstrated that the TAPS prototype and the acoustic sensor both measured the TAPS resonance frequency at 1407.2 Hz and confirmed that they were working properly.

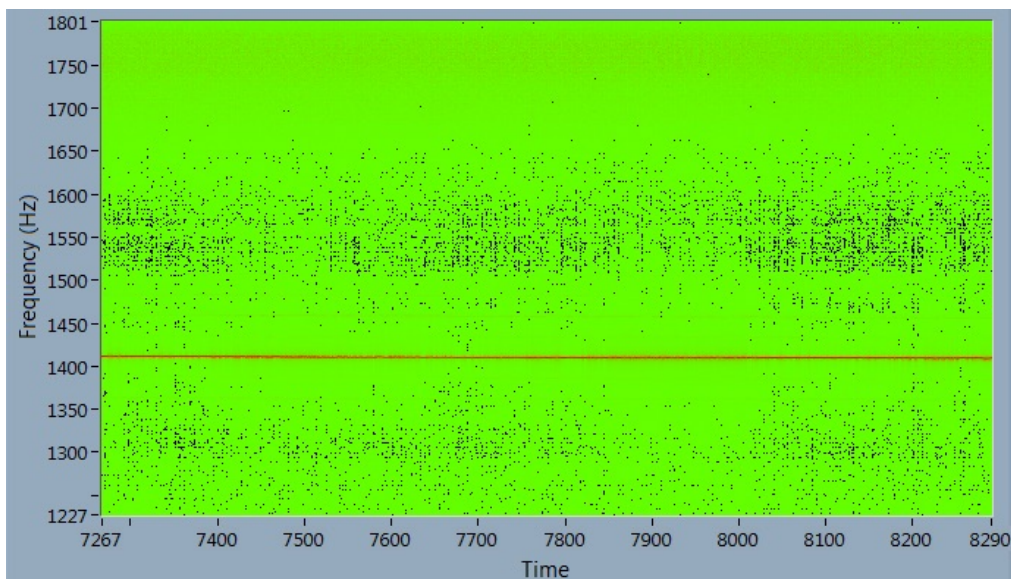


Figure 25. Spectrogram of the TAPS prototype inside the test vessel under ambient condition.

6 DISCUSSION AND CONCLUSIONS

Argonne received a TAPS prototype from Westinghouse and the prototype was modified such that it can be installed into the test vessel and work in sodium at elevated temperature without potentially causing sodium leaking. The Swagelok fittings used to connect a bellows in between the prototype and the holding tube were removed and the three parts are now welded together. A water mockup test apparatus was constructed to validate proper functioning of the prototype. An instrumentation and control (I&C) system, running on the NI LabView platform, was developed to operate both the water mockup test and the in-sodium test facility. The system is able to select and control different inputs from different NI DAQ modules, acquire digitized signals, process and analyze the signals, and display the control parameters and results (temperatures, spectra, and spectrogram). The prototype was successfully tested in a water bath with temperature ascending or descending continuously between ambient to 97°C. Water mockup tests demonstrated that the TAPS prototype is working properly and its resonance frequency changes linearly with the coolant (water) temperature.

The design and construction of a TAPS test apparatus and the modification of the Argonne USV sodium test facility were completed. The TAPS test apparatus was also successfully integrated with the Argonne USV sodium test facility. The TAPS prototype developed by Westinghouse and a sodium-submersible high-temperature acoustic sensor developed by Argonne are both installed in the TAPS test vessel. Both sensors were tested successfully after leak testing of the TAPS test apparatus. Under the ambient condition and within argon cover gas, the preliminary tests clearly demonstrated that both sensors detected the TAPS resonance frequency at 1407.2 Hz, which confirms that the TAPS prototype and the two sensors are working properly.

The in-sodium test of the TAPS prototype has been delayed due to the modification, construction, and integration of the USV sodium test facility and the TAPS and ISHM test apparatuses, as well as the formal safety review and operating approval of the USV-TAPS-ISHM sodium test facility. The sodium test facility is currently at a standby condition and is purged with argon cover gas at a pressure slightly higher than the ambient (~2 psig). Before transferring sodium, the secondary containment will be filled with vermiculite for thermal and electric insulations. Sodium will be transferred into the vessel for in-sodium testing, once the facility is approved for operation. Nevertheless, the results of the water mockup tests and the preliminary tests done within argon cover gas clearly demonstrate that the TAPS technology has the characteristics to provide continuous self-powered measurement and monitoring of the power level, power distribution, and temperature distribution of an SFR core accurately and in real-time, using sensors positioned either outside or inside the core.

7 FUTURE WORK

Argonne will continue the development and evaluation of the TAPS prototype for real-time measurement and monitoring of power level, power distribution, and temperature distribution of an SFR core. Argonne will conduct in-sodium testing of the Westinghouse TAPS prototype at elevated temperatures under stationary and dynamic modes. The performance evaluation covers the following four major subtasks:

Tap Testing:

Tap testing was suggested by Westinghouse to identify the fully-coupled resonant frequencies of the vibroacoustic system constituted by the vessel, TAPS, fluid, vessel supporting structure, etc. Before and after introducing sodium to the vessel, using an impulse hammer to tap at designated input points on the vessel structure and nearby the accelerometers. The vibrational modes of the structural-acoustic system are expected to be temperature-dependent, and direct measurement allows for corroboration of the FEA modeling and when post processing operational TAPS test data.

Signal Optimization:

To determine the optimal signal conditioning, including amplification, filtering, and processing according to the operating condition and resonance frequency range.

TAPS Prototype Validation and Verification:

After introducing sodium to the vessel, using accelerometers and the Argonne high-temperature acoustic sensor to

- verify if the TAPS prototype works properly;
- validate resonance frequency of the TAPS prototype; and
- determine the onset point of thermoacoustic effects at different sodium temperatures and the electric heater temperatures (or input power).

Flowrate Effect Evaluation:

To evaluate the flowrate effect, in-sodium tests will be conducted under dynamic and stationary mode, i.e. with the EM pump on and off. The resonance frequencies of the TAPS and amplitude of the acoustic signals will be compared at different sodium temperatures and different flowrates.

TAPS Prototype Performance Evaluation:

To determine the sensitivity, response time, and reproducibility of the TAPS prototype under different power settings of the electric heater, different flowrates, and different sodium temperatures. A test matrix will be generated for steady-state power testing, quasistatic flow, and elevated temperatures at several increments or in continuous fashion if applicable.

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2. Westinghouse Internal Report, RT-FR-15-001, *Functional Requirements for Thermo-Acoustic Sensor System for Sodium-cooled Fast Reactors*, June 2015.

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